Nuclear Reactions for Astrophysics at NIF Using Radiochemistry "Thoughts"

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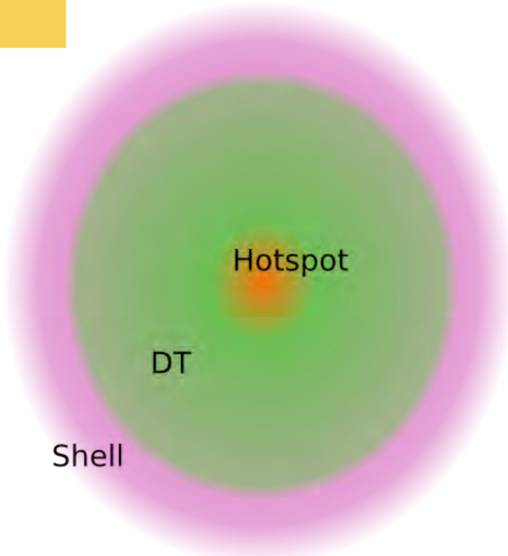
High Fluence of both Neutrons and Charged-Particles Induce Reactions off the line of stability

Allows multiple reactions on materials loaded in the shell
=> Reactions on short-lived unstable targets

- First neutron reactions to get off line of stability
  (n,2n), (n,3n) or double (n,2n) for proton-rich
  (n,γ) for neutron-rich



- Followed by charged-particle reactions of interest
  e.g., (p,γ), (p,α), …

Caveat: NIF design physicists warn that doping is possible ***iff*** achieve robust ignition

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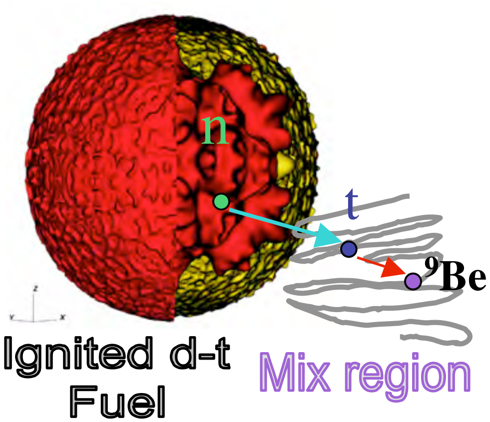
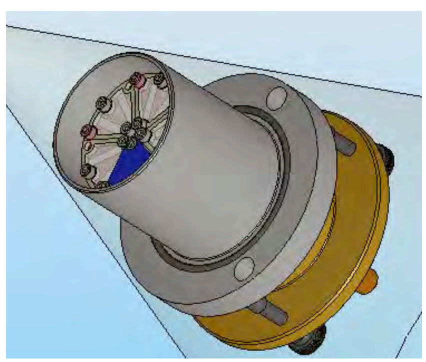
Currently Developing Diagnostic for Mix and Instabilities in Ignited NIF Capsules

Scheme based on using double reactions: n+t $\longrightarrow$ t*(knock-on)
t+shell $\longrightarrow$ X(β-)

Detect

Triton interactions with shell material ~100mb. Mix diagnosed by observing beta decays of resulting isotopes, after target disassembly.





Triton + ^{9}Be ablator (t,α) reactions distinguish different types of mix.

$t + {}^{9}Be \rightarrow \alpha + {}^{8}Li + \beta$ (13 MeV, 840 ms)

NIF full Yield - ^{8}Li production

No Mix	Chunk Mix	Atomic Mix
1×10^{12}	3×10^{12}	1×10^{14}

Debris collector & β counter.

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Thoughts on using similar techniques for Nuclear Astrophysics

- How far off the line of stability can we go?
- What can we do that we can't do at a radioactive ion beam facility?
- How do we detect the reactants?
- How many reactions do we need for collection/detection?
- Which reactions are feasible?
- How do extrapolate from NIF flux-average the cross section to those needed of astrophysicist?

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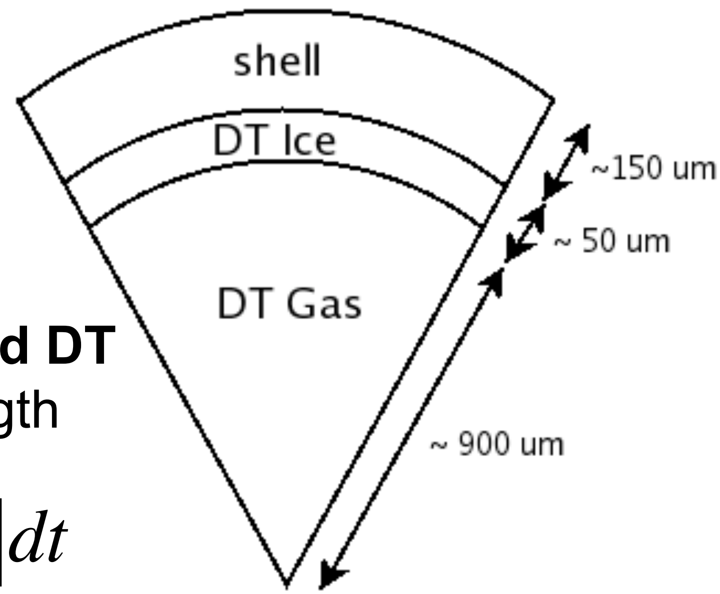
Physics Parameters for Ignited Capsule

Examined a high yield DT capsule with ^{9}Be(.9%Cu) ablator/shell

Clean yield 16.65 MJ => 6x10^{18} DT reactions, ~ 6x10^{18} neutrons

$\langle\rho r\rangle_{shell}$ = 0.25 g/cm^2
range = .1 - .6 g/cm^2

$\langle\rho r\rangle_{capsule}$ = 1.2 g/cm^2



Also examined mixing between shell and DT
Mix varied as a parameter - the mixing length

$$L = \alpha \int \left| \; u_{DT}(r,t) - u_{shell}(r,t) \; \right| dt$$

α=0.06 => Y= 9.5 MJ
α=0.12 => Y= 5.2 MJ

Reaction estimates scale with yield and $\langle\rho r\rangle$

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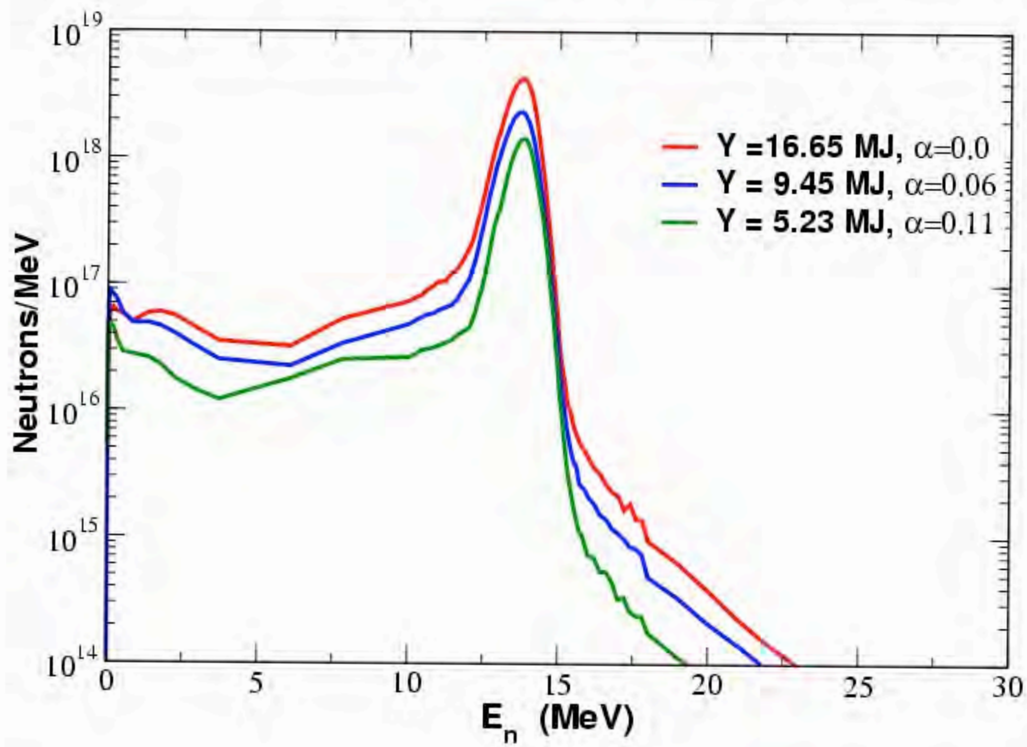
Neutron Spectrum

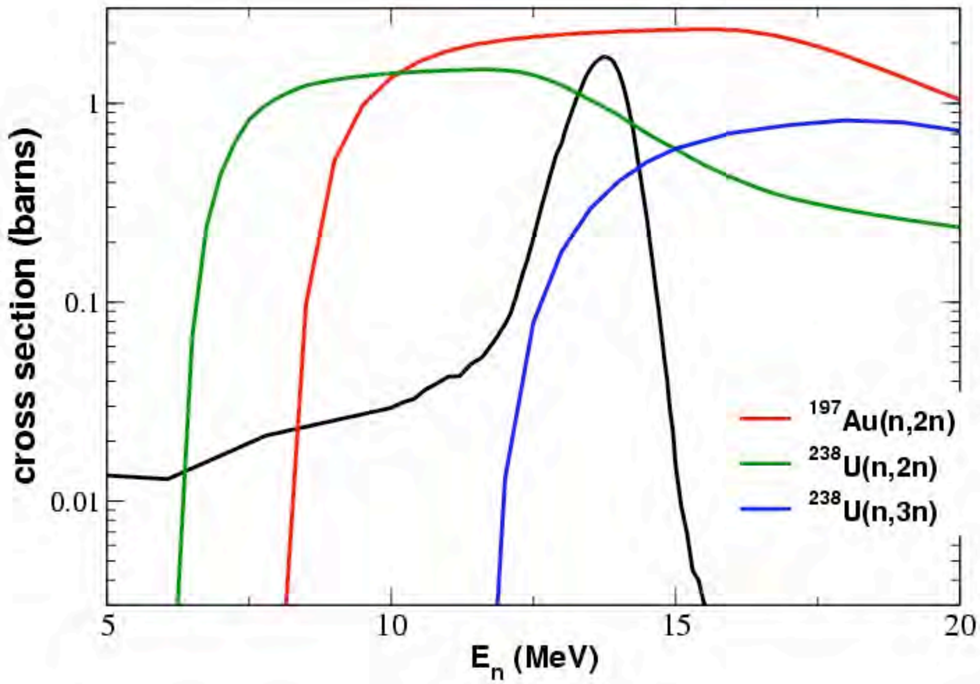
Neutron spectra at DT fuel/shell interface

Different yields and shell/fuel mixing result in similarly shaped spectra

10% < 14 MeV peak
0.3% > 14 MeV peak (RIFs)



Neutron Reactions



(n,2n) reactions best potential
Typical cross sections ~ 1b at 14 MeV

Single (n,2n) ~ 10^{16} reactions
Double (n,2n) ~ 10^{12} -10^{13} reactions

Some heavy nuclei (n,3n) ~ 1b@ 14 MeV

However, for many nuclei of interest neutron binding is high
=> (n,2n) threshold > 14 MeV

e.g., ^{32}S; ^{24}Mg, ^{16}O; ^{19}F, ……

$10^{16} \longrightarrow$ ~ 10^{13} or less

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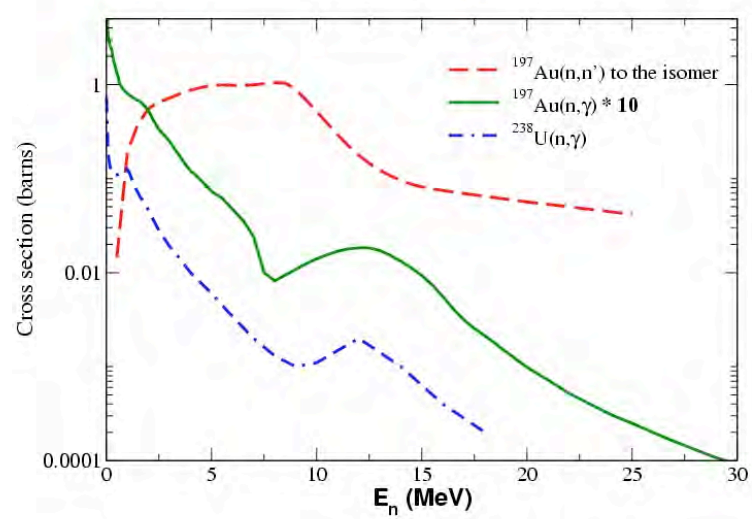
Other Neutron Reactions also Possible

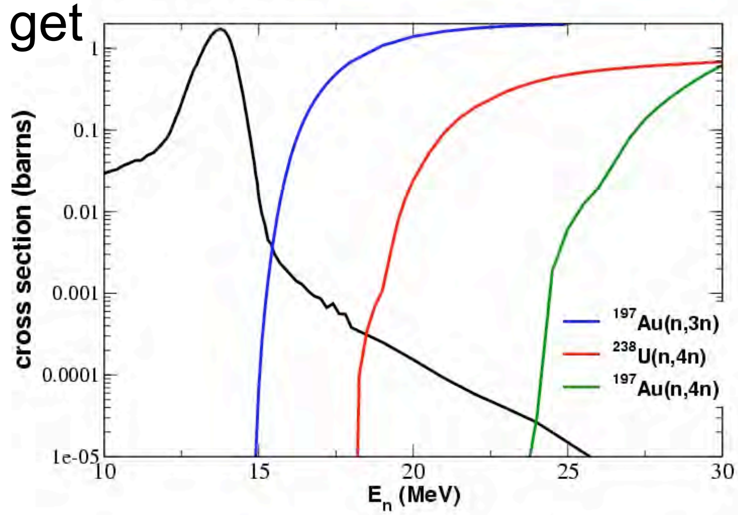
- The so-called direct-semi-direct contribution to **neutron capture** yields a capture cross sections ~ 1mb @ 14 MeV
  => ~ 5x 10^{13} reactions



- **Inelastic (n,n') scattering to isomers**
  => $3x10^{15}$

- **Threshold for (n,3n) is often too high** to get a significant number of reactions

- Double (n,2n) often better



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Charged Particle Fluences

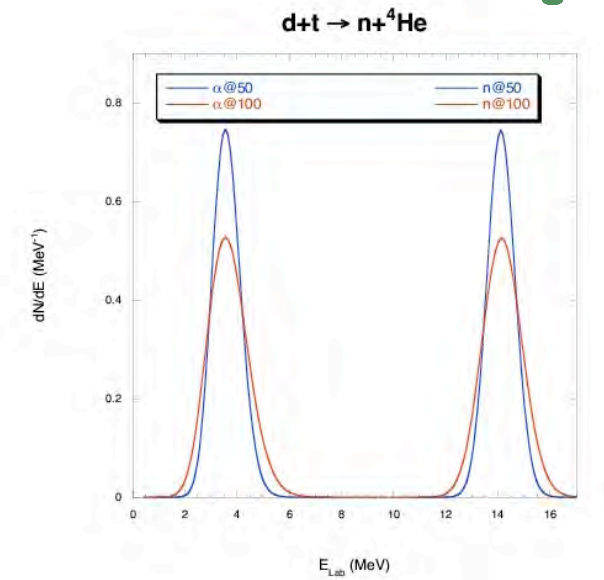
Main Reactions

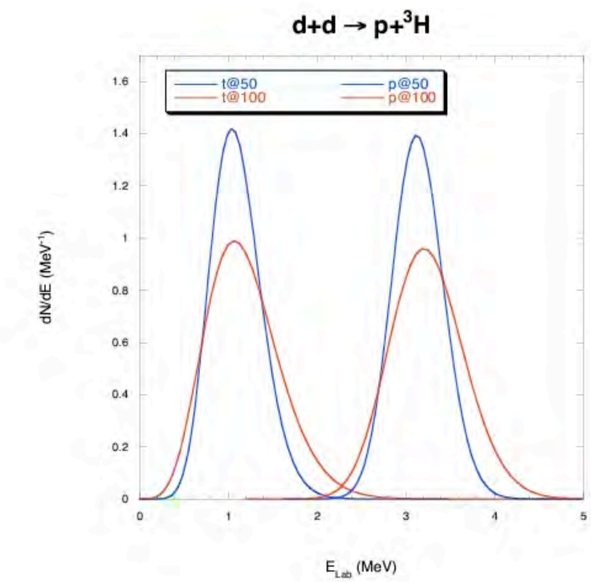
d + t	$\longrightarrow$	n(14.1) + ^{4}He(3.5)
d + d	$\longrightarrow$	n(2.45) + ^{3}He(0.82)
d + d	$\longrightarrow$	p(3.02) + t(1.01)
t + t	$\longrightarrow$	2n + ^{4}He (spectrum of energies)
d + ^{3}He	$\longrightarrow$	p(14.7) + ^{4}He(3.65)
t + ^{3}He	$\longrightarrow$	d(9.55) + ^{4}He(4.77)

Produce large fluence of energetic (MeV) p, d, t, ^{3}He, ^{4}He

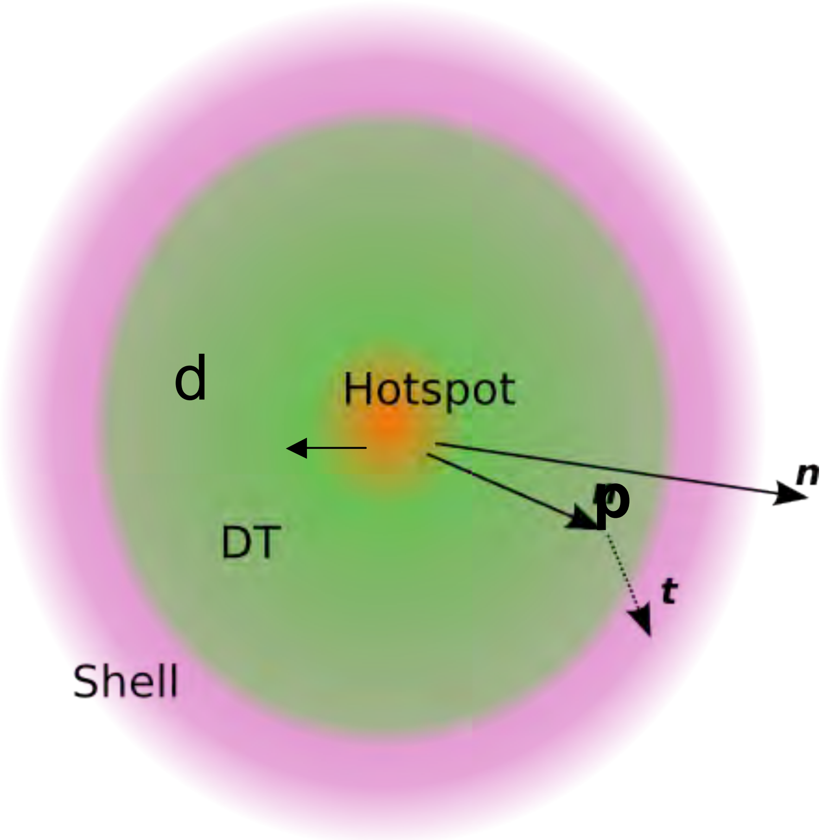
Can retain significant fraction of this energy upon reaching the ablator

Thermal Broadening





Charged-Particle Fluence in the Shell



At the fuel-shell interface

n	6×10^{18}	14.0 MeV
α	3×10^{18}	0.4 MeV
p	1×10^{17}	2.3 MeV
t	4×10^{17}	0.5 MeV
d	3×10^{17}	1.2 MeV

Outer surface of ablator

n	5×10^{18}	14.0 MeV
α	~ 0	0
p	3×10^{15}	~50 keV
t	few	~10 keV
d	1×10^{16}	~50 keV

Energetic p and d can traverse the shell

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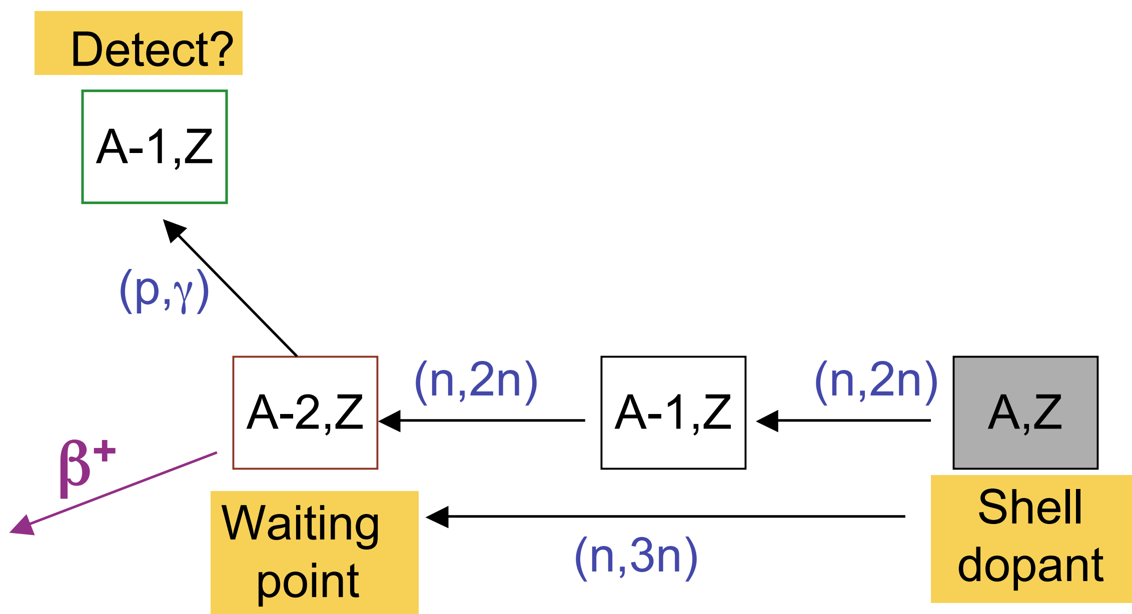
Example

Want to measure (p,γ) and (p,α) on unstable waiting point nucleus



Non-thermal charged particle Reactions

- A significant fraction of charged-particle reactions can take place before thermalizing

- Energetic (MeV) cross-sections can be orders of magnitude larger than thermal

- Stopping and Non-Maxwellian component of charged-particle spectrum need to be understood in detail

- Probably need full Monte Carlo treatment of charged-particle transport & reaction

Number of charged-particle Reactions Produced depends on energy & stopping

Stopping Length:

$$L \simeq \frac{2\theta_e^{3/2} E_0^{1/2}}{c_R n_e}$$

Probability of particle with energy E reacting:

$$P(E) \approx \hat{n} \int_0^E dE' \frac{\sigma(E)}{-(dE/dx)_{shell}} \approx 2\frac{n\theta_e^{3/2}}{n_e C} \int dE' \frac{\sigma(E)}{\sqrt{E}}$$

Need to integrate this over energy distribution of charged-particles in the shell

Ratio of density of unstable targets to electrons n the shell ~ 10^{-5} - 10^{-6}

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Count Estimates

Dope shell with A (stable) (say 33%)

- A*(n,2n)*A-11*(n,2n)*A-2
  => ~ 10^{12} produced, if both (n,2n) cross section 1b

10^{17} protons at fuel/shell interface <Ep> ~ 2.3 MeV

3×10^{15} protons make it to outer surface of shell $\langle E_p \rangle$ ~ 50 keV

- **Get ~ 10^5 reactions assuming a 10mb cross section**

  - *(integration over p spectrum and stopping preliminary)*

- Simplified estimate: $N_p \langle \rho r \rangle$ (A-2/A atoms) σ = 5×10^4 reactions

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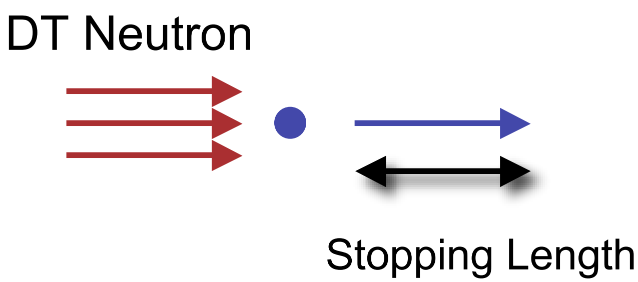
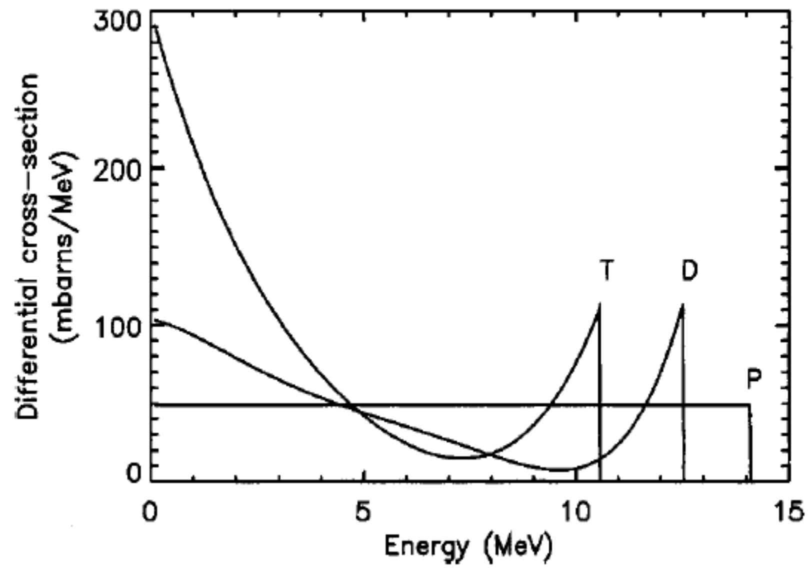
Up Scattered Charged-Particles Observed at Omega



$$\frac{d\psi_t}{dE} = \frac{\theta_e^{\frac{3}{2}}\psi_n n_t}{c_R n_e \sqrt{E}}\sigma_{nt}(\geq E)$$



Produce p,d,t with E> 10 MeV

Escape the capsule and detected

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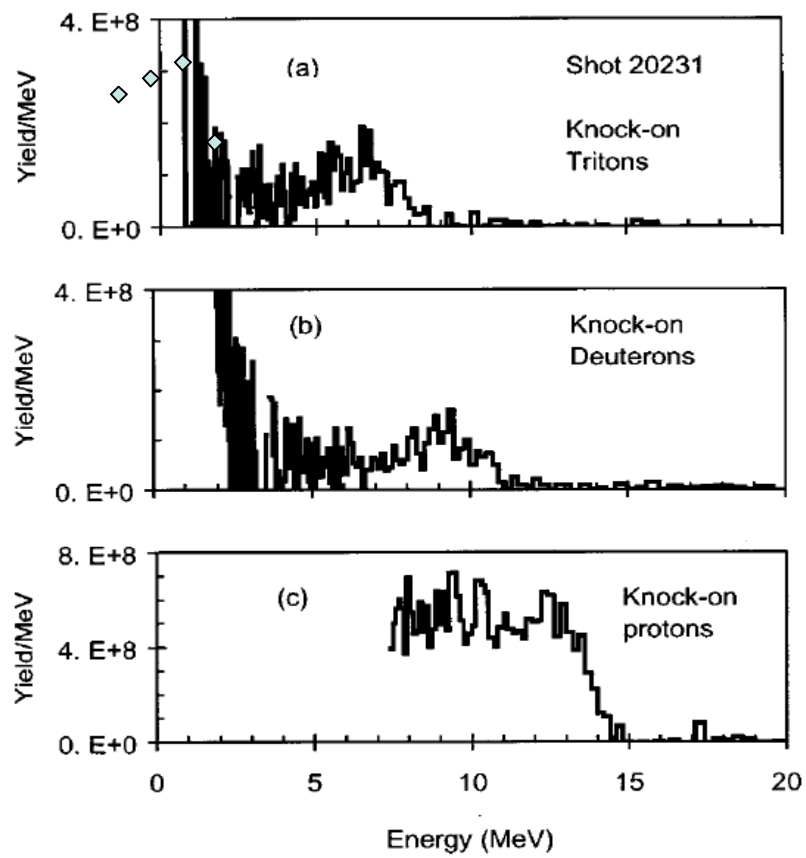
Emitted charged-particles are Strong constraint on predicted charged-particle transport, stopping, etc.

$<\rho r>_{shell} \sim 35\ mg/cm^2$

Knock-on tritons at Omega predicted to loose about 3.45 MeV traversing the shell

In reasonable agreement with experiment



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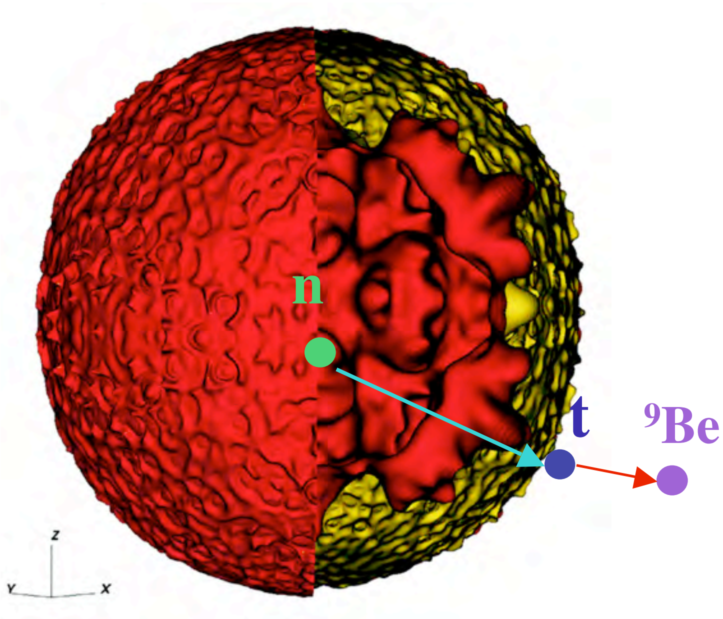
Ongoing Experimental Program Beta-Mix

MeV Triton interaction with shell material ~100mb.
Observe beta decays of resulting isotopes, after target disassembly.



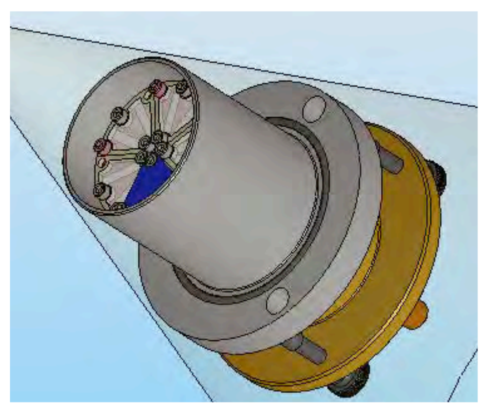
Ignited d-t Fuel

Main Reactions

NIF: $^{9}\mathrm{Be}(t,\alpha)^{8}\mathrm{Li}$ (β^-, 840ms)
$^{9}\mathrm{Be}(t,p)^{11}\mathrm{Be}$($\beta^-$, 13.8s)

Omega: $^{13}\mathrm{C}(t,p)^{15}\mathrm{C}$($\beta^-$, 2.5s)
$^{13}\mathrm{C}(t,\alpha)^{12}\mathrm{B}$($\beta^-$, 21 ms)

All high-energy β's ~ 10 MeV



Debris collector & β counter.

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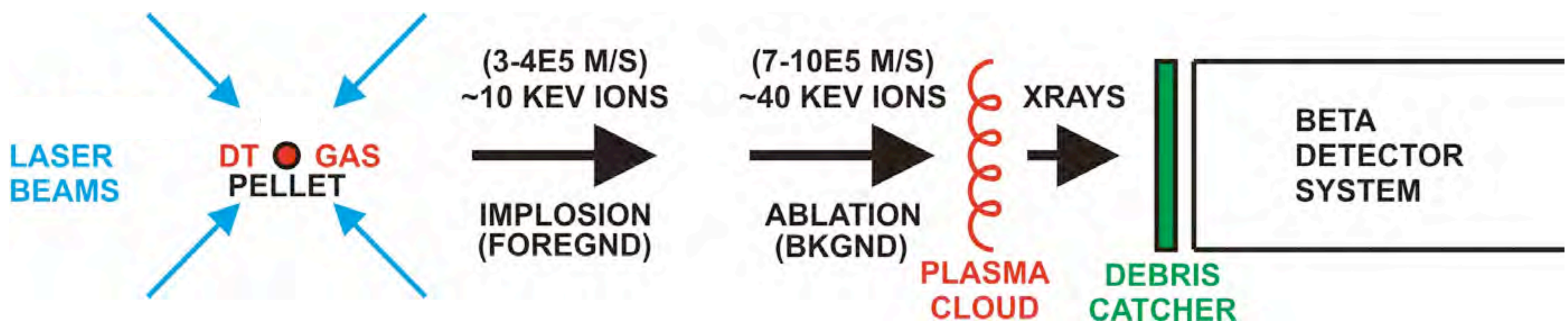
DEBRIS COLLECTION CHALLENGES

- Need high efficiency and sufficient solid angle.
- Induced radioactivity must be low.
- Must survive the radiation and shock wave.
- Must be able to assay debris fraction i.e., bomb fraction.
- Overcome hohlraum issues



430 ns	160 ns	0.5 ns	Omega (15 cm)
2900 ns	1000 ns	3.5 ns	NIF (1 m?)

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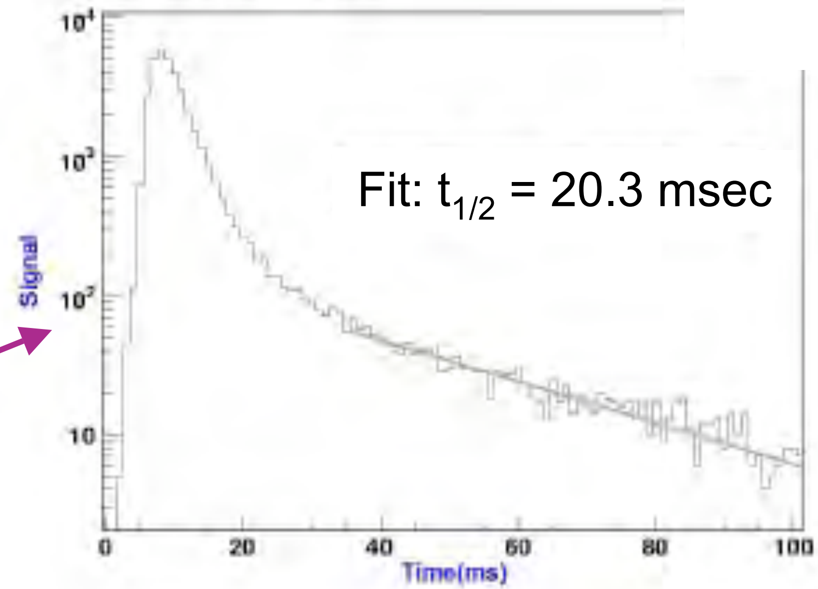
Progress using the Omega Laser Facility

➢Fielded β-detector with 30 ms recovery

➢Observed β-decays with half-lives as short as ^{12}B



➢Preliminary measurement of 300 μb, $^{12}C(n,p)^{12}B$ cross section at 14 MeV.

➢Observed ^{15}C *(2.45 sec β-)* from the $^{15}N(n,p)$ reaction - extracting cross section

➢First debris collection experiments fielded using labeled ^{13}C targets.

➢Debris collector mass measurement sensitivity better than 0.5 nanograms.

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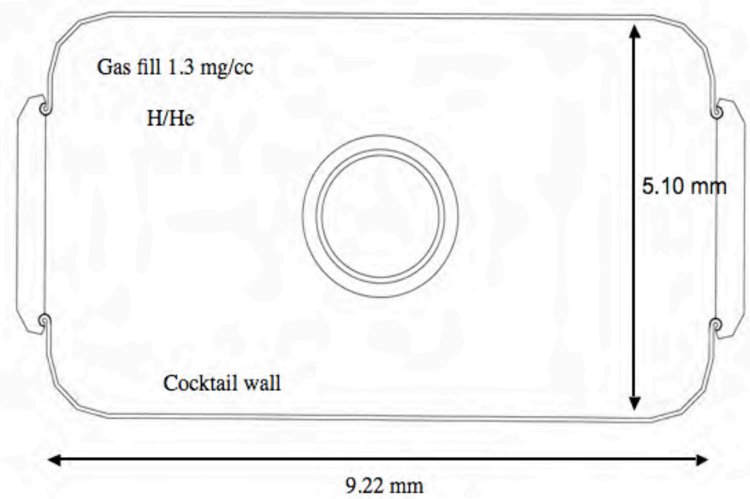
Reactions in the Hohlraum

• Baseline design is cylindrical 75%U, 25%Au cocktail

• Wall thickness is 30μm, of which 7μm is the cocktail

• Possible to use other materials for the wall backing without affecting the yield



10^{19} neutrons => ~10^{15} reactions for 1b cross section
~10^{11} for double reactions

Summary

- Fluence of neutrons and charged particles suggest that double and triple reactions produce significant yields
- Reactions of interest very challenging - triple reactions maybe too small
- Significant progress being made to develop experimental techniques at Omega
- Can measure reaction products with lifetimes ~ tens msec
- Energetic of charged-particles traversing the shell high
- Need accurate tools to extract the desired thermal cross sections from flux-averaged measurements
- Reactions in the hohlraum may be a possibility

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